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SAMPEX Observations of Anomalous Cosmic Rays Trapped in the Magnetosphere

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The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX), launched July 3, 1992, into an 82 degree inclination, low-Earth orbit (670 × 520 km), is the first of NASA's new line of Small Explorer (SMEX) missions. SAMPEX has been described in *U.S. STEP News*, Vol. 1, No. 6, December 1991. The spacecraft carries four instruments designed to measure the composition of energetic nuclei and electrons over a broad range in energy and intensity, including particles of solar, interplanetary, galactic, and magnetospheric origin. A detailed description of the spacecraft and these instruments is given in the May 1993 issue of *Geoscience and Remote Sensing*. Of the many studies that SAMPEX has conducted during its first year of operation, one of the most interesting has been of a trapped radiation belt encircling the Earth that contains high-energy N, O, and Ne nuclei from the local interstellar medium. These observations, along with earlier work from a series of COSMOS satellites, confirm a prediction made more than a decade ago. The process by which interstellar material finds its way into the magnetosphere involves a rather fascinating series of steps.

The four SAMPEX instruments include a Low-Energy Ion Composition Analyzer (LEICA) from the University of Maryland, a Heavy-Ion Large Telescope (HILT) built by the Max-Planck Institut fur Extraterrestische Physik and the Aerospace Corporation, and a Proton Electron Telescope (PET) and Mass Spectrometer Telescope (MAST) built by Caltech and Goddard Space Flight Center. The MAST team includes the authors of this article and A. C. Cummings, R. A. Leske, R. S. Selesnick, E. C. Stone, and T. T. von Rosenvinge. The MAST instrument, used for the observations reported here, consists of an array of silicon solid-state detectors designed to measure the elemental and isotopic composition of ~15 to ~200 MeV/nuc energetic nuclei from He to Ni (nuclear charge Z = 2 to 28), including solar energetic particles and cosmic rays that are accessible over the polar regions of the SAMPEX orbit.[1] However, with the exception of two large solar flare events, trapped particles have been the dominant source of ions with Z>2 observed by MAST during its first year in space.

Figure 1 below shows the geographic location of 16 to 200 MeV/nuc oxygen nuclei observed by MAST during solar quiet periods from 1992 Day 187 to 1993 Day 38. In the polar regions MAST observes cosmic rays as well as low-energy solar and interplanetary particles extending down to the latitude allowed by the local geomagnetic cutoff. Also evident in Figure 1 is a concentrated band stretching from the tip of South America to the southern tip of Africa, just south of the well-known South Atlantic Anomaly (SAA). The ions in this band are observed only when MAST is viewing at right angles to the local magnetic field, confirming that this is a trapped population with pitch angles of ~90 degrees.

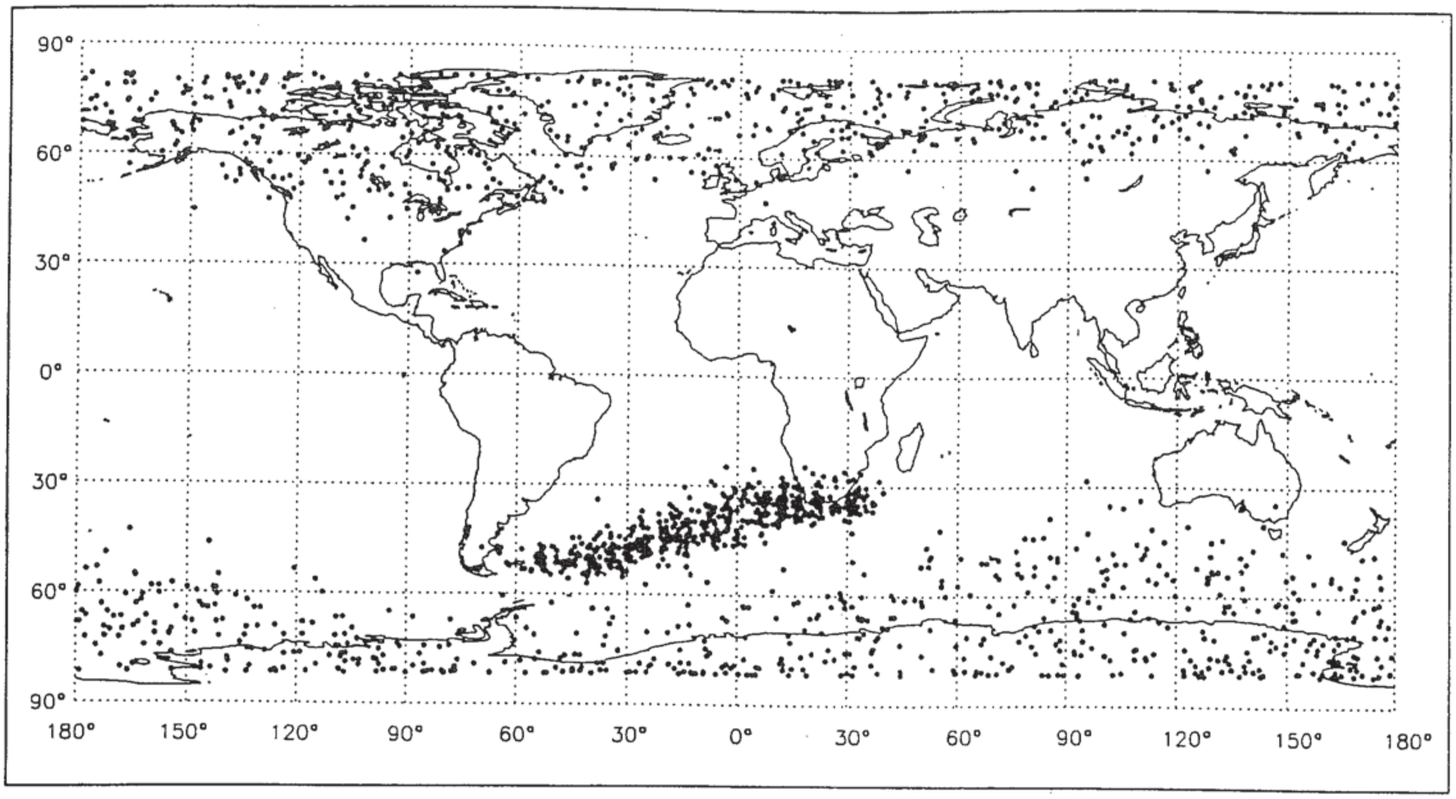

Figure 1 : Geographic distribution of quiet-time oxygen nuclei with 16 to 200 MeV/nucleon observed by MAST during the period from 1992 Day 187 to 1993 Day 38.

As suggested by Figure 1, the trapped O is located in a rather narrow band of magnetic L shells. Figure 2 below shows the invariant latitude and corresponding L-shell distribution of 16 to 30 MeV/nuc oxygen, and Figure 3 below illustrates the relation of this new belt to the well-known Van Allen belts. In addition to O, the new belt also includes N and Ne ions (see Figure 4 below). Although trapped He ions are also observed in this region, they have a somewhat different L-shell distribution and temporal behavior and most likely have a different origin.

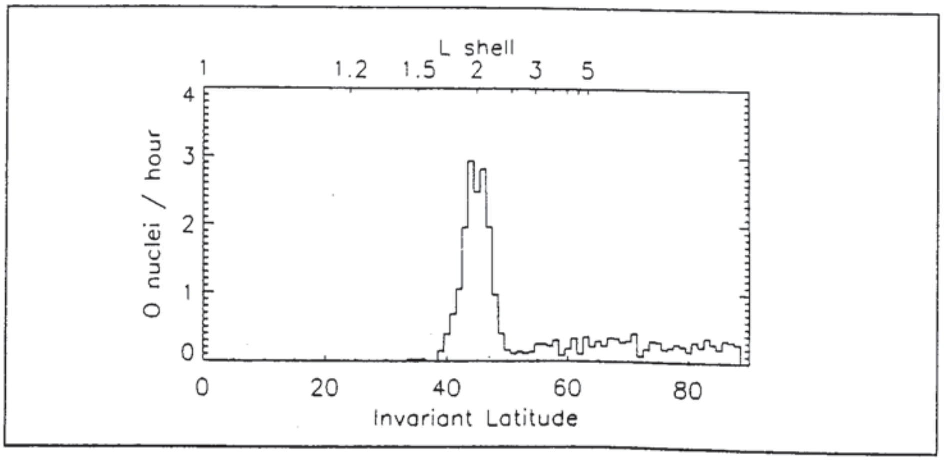

Figure 2: Invariant latitude distribution of quiet-time 16-30 MeV/nuc observed by MAST. For comparison, the SAA is centered approximately at ~30 degrees so latitude and ~315 degrees longitude.

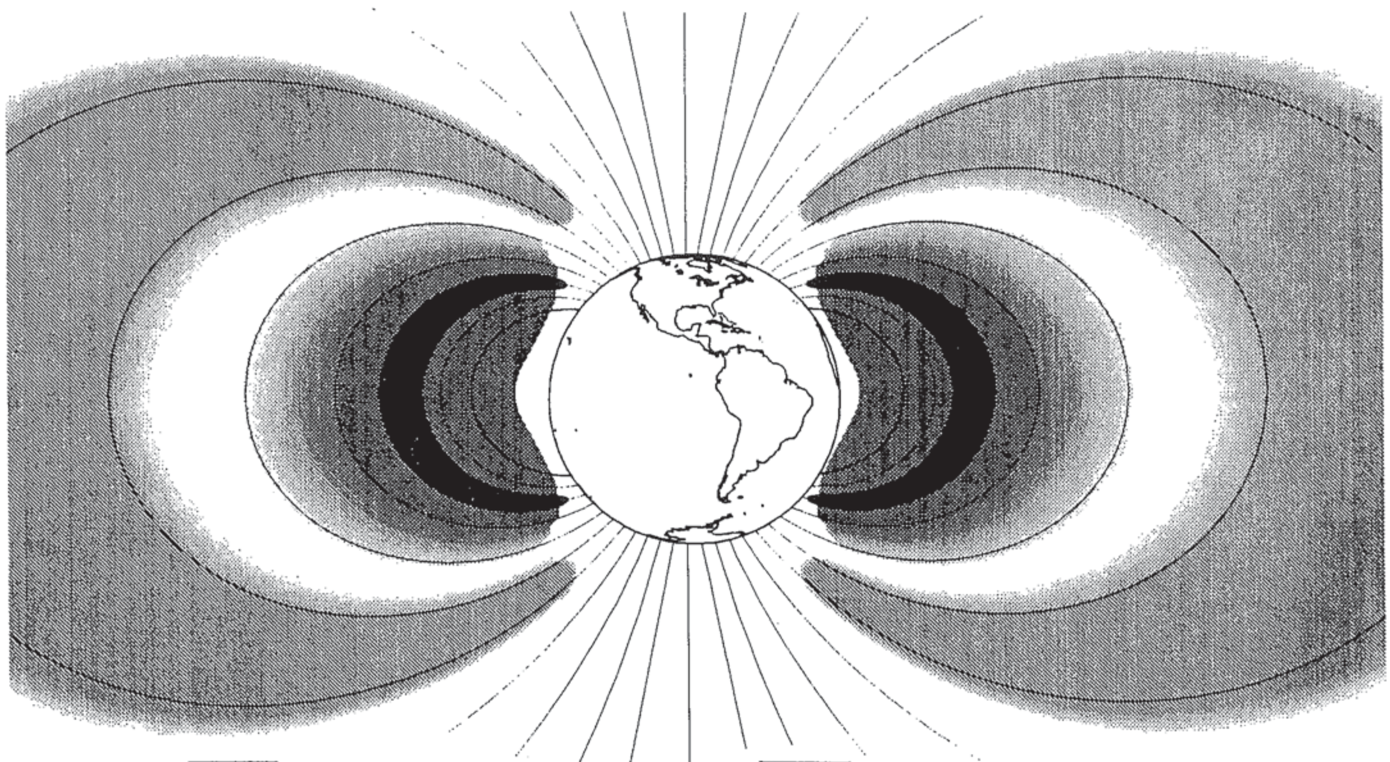

Figure 3: The new radiation belt is shown as a dark gray crescent at L~2 imbedded in the inner of the two Van Allen belts (lighter gray crescents).

Composition of Trapped Nuclei is Key to Origin

The composition of nuclei observed within this belt (see Figure 4 below) is rather unusual with relative abundancies of <0.004:0.11:1:0.025 for C:N:O:Ne. This C/O ratio is considerably less than in typical populations of energetic nuclei in the solar wind and solar energetic particles (where C/O ~ 0.4) or in Galactic cosmic rays (where C/O ~ 1). The significant Ne abundance argues against an atmospheric origin (where Ne/O ~ 5×10^{-5}); however, the observed composition is very similar to that of the low-energy "anomalous" cosmic ray component thought to be accelerated at the solar wind termination shock. For example, Voyager observations at 23 AU in 1987 found C:N:O:Ne = 0.01:0.17:1:0.055.

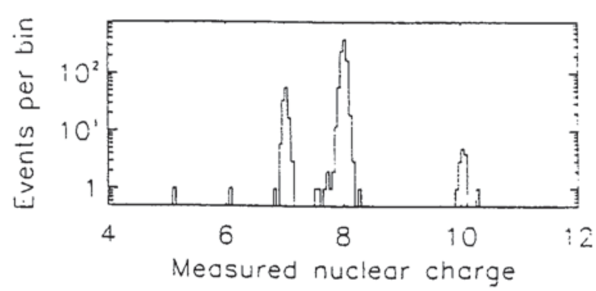

Figure 4: Observed composition of trapped nuclei with Z>4 at L = 2.05 ± 0.60, including all days from 7/6/92 to 2/7/93. Detection thresholds in MAST range from ~14 MeV/nucleon for C to ~16 MeV/nucleon for O to ~18 MeV/nucleon for Ne. In addition, one event with Z = 23 was observed.

SAMPEX Observations (continued)

Anomalous Cosmic Rays - Sample of the Neutral Interstellar Medium Accelerated to High Energies

In order to understand how "anomalous cosmic rays" (ACRs) get trapped in the magnetosphere it is instructive to review their properties.

During the mid-1970s, experiments on Pioneer 10 and IMP 5 and 7 discovered anomalous enhancements in the low-energy (<50 MeV/nuc) spectra of a number of elements, including He, N, O, and Ne. The unusual composition (O exceeded C in abundance by ~30 to 1 and He exceeded H) led to the name "anomalous cosmic rays" for this new energetic particle component. The intensity of ACRs was found to be very sensitive to the effects of solar modulation, and a large, positive radial gradient in intensity was observed as the Pioneer 10 and 11 spacecraft moved into the outer heliosphere. More recent observations by Voyager 1 and 2 in the outer heliosphere have shown that the flux of ACRs varies by a factor of ~10E2 to ~10E3 over the solar cycle, and that there are also ACR contributions to the energy spectra of C, Ar, and possibly H.

The Origin of Anomalous Cosmic Rays

Soon after the discovery of ACRs, Fisk et al.[2] proposed that they represent interstellar neutral particles that have drifted into the heliosphere, been ionized by solar UV or by charge exchange with the solar wind, convected by the solar wind into the outer heliosphere, and then accelerated to high energies. Once accelerated, they can make their way back into the inner heliosphere as cosmic rays. It is now believed that the acceleration takes place at the solar wind termination shock, following a suggestion by Pesses, Jokipii, and Eichler.

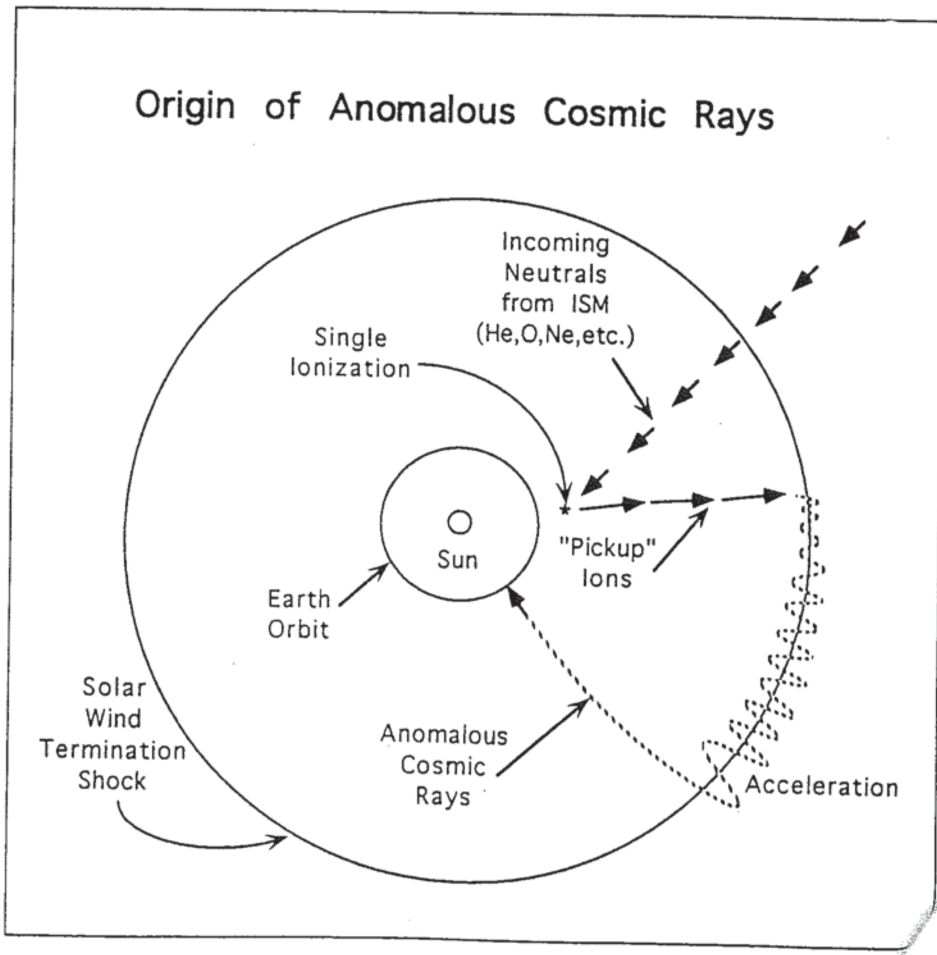

Figure 5: Illustrated Origin of Anomalous Cosmic Rays.

SAMPEX Observations (continued)

The model described above and illustrated schematically in Figure 5 above explained the unusual composition of ACR nuclei (only those elements that are predominantly neutral in the interstellar medium) and it made the important prediction that anomalous cosmic rays should be singly-charged, in contrast to Galactic cosmic rays, which are essentially fully-stripped. Although there has been considerable indirect evidence that this is the case, it was not until the last few years that observations using the Earth's magnetic field as a rigidity filter provided direct evidence that ACRs are indeed singly-charged. In the meantime, there are now also direct observations from ISSE 3 and ULYSSES of the singly-ionized interstellar particles that have been swept up by the solar wind (so-called "pickup" ions) and ULYSSES has made direct observations on neutral He atoms that have penetrated into the inner solar system.

In 1977, Blake and Friesen[3] proposed that if ACRs are indeed singly-charged, they could be trapped in the Earth's magnetic field. They reasoned that this trapping could occur if a singly-charged ACR with a rigidity somewhat above the local geomagnetic cutoff penetrates sufficiently deep to skim the upper atmosphere and lose some or all of its remaining electrons, such that its resulting rigidity was suddenly below the trapping limit (see Figure 6 below). They predicted that these trapped ACRs would be located at L = 2.5 to L = 3.5, and that they might have a lifetime of perhaps weeks, permitting a significant trapped population to build up and be sustained. This mechanism is expected to trap heavy ACR nuclei like N, O, Ne, and Ar, but not He.

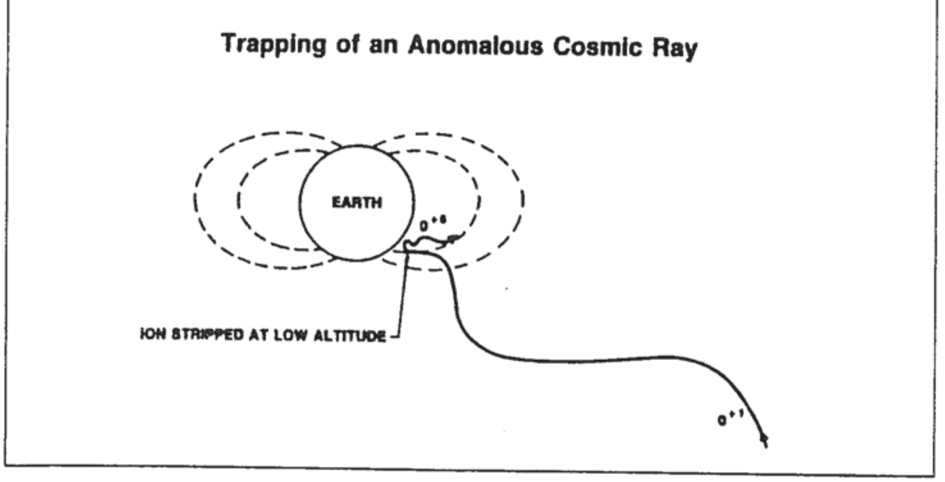

Figure 6: Illustrated mechanism for trapping anomalous cosmic rays.

COSMOS Observations at the Last Solar Minimum

The first evidence for the existence of trapped ACRs was provided by a team of Russians and U.S. scientists using observations from a series of COSMOS satellites.[4] In that study passive track detectors were launched approximately monthly during the 1985 to 1988 solar minimum, typically returning to Earth after two-week flights. Subsequent analysis of the track detectors revealed ~5 to 30 MeV/nuc ions with a composition, angular distribution, and temporal behavior consistent with the expected properties of trapped ACRs. However, the passive detectors on COSMOS could not measure directly the ions' spatial distribution. The COSMOS data showed that the intensity of trapped O decreased dramatically with the onset of increased solar activity in 1987-1988, consistent with the interplanetary flux of ACRs observed by IMP 8.

SAMPEX Observations (continued)

When SAMPEX was launched in 1992 our team expected a one- to two-year wait until ACRs would be observable at 1 AU with the approaching solar minimum. It was, therefore, a pleasant surprise when the now-familiar ACR fluxes were already observable by MAST in the first months following launch, with an intensity five- to ten-times greater than that at similar neutron monitor counting rates during the 1970-71 and 1984-1985 recovery periods. This early return of ACR nuclei to 1 AU in 1992 also appears to have re-populated the radiation belt at L~2, and trapped ACR oxygen nuclei were evident in the first few days of MAST data following the SAMPEX launch.

A Leaky "Magnetic Bottle" Containing Interstellar Material

In addition to confirming the Blake and Friesen mechanism and the COSMOS observations, the SAMPEX data also provide a much more detailed picture that is revealing some important differences. The location of the belt is actually much closer to the Earth (at L~2) than was predicted by Blake and Friesen (L~2.5 to 3.5), and it is much narrower in extent. Oxygen nuclei with a given energy per nucleon are observed over only a very limited range of L-shells; the lower limit appears to correspond to the lowest L-shell accessible to singly-charged ions (taking into account the geomagnetic cutoff to the west, while the upper limit apparently corresponds to the maximum L-shell where stable trapping is allowed. To date, MAST has observed trapped oxygen ions extending to >50MeV/nuc with a very steeply-falling energy spectrum.

In essence, this new radiation belt corresponds to a "magnetic bottle" that holds a sample of interstellar material. However, because the bottle has a leak (the ions slowly lose energy to the thin upper atmosphere at their mirror points), the amount of material in the bottle is a balance between this leak and the rate at which it is being filled. The rate of flow into the bottle varies with the solar modulation of the anomalous cosmic rays, and as a result, the intensity of ions trapped in the bottle varies by perhaps a factor of ~10E3 over the solar cycle, such that it may not be observable at solar maximum. At present the intensity of ACR oxygen inside the bottle is >100 times that in interplanetary space, and as the interplanetary ACR intensity increases during the approach to solar minimum (and the drag of the upper atmosphere decreases), we can expect the intensity of ions trapped in the bottle to increase by as much as an order of magnitude. Thus, SAMPEX observations over the next few years should provide a unique opportunity to use this radiation belt to study magnetospheric processes, and to examine the elemental and isotopic composition of a sample of interstellar matter that (on a Galactic scale) is located right in our own back yard.

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